Numerical Studies of Acoustic Propagation in Shallow Water

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LONG-TERM GOALS

To develop "exact" numerical methods and visualization techniques that can be used to study the propagation of acoustic energy in shallow water in the time domain. Exact in this contexts means the methods place no restrictions on the underlying physics of the environment.

OBJECTIVES

To develop new, and enhance existing, numerical methods; to establish the accuracy, robustness, flexibility, and tractability of these methods; and to apply these methods to meaningful practical problems. To create a robust software suite for the application of the methods and to develop techniques for visualizing the propagation of scalar and vector fields in complex environments.

APPROACH

We have focused our attention on the development and use of finite-difference time-domain (FDTD) methods. These time-domain techniques, which are flexible, robust, and generally simple to implement, have previously been used by the electromagnetics community to solve a wide range of problems. However, FDTD methods have not been widely used by the acoustics community and, thus, the ability of these methods to solve accurately many of the problems related to propagation in a shallow water environment is the subject of continuing research.

WORK COMPLETED

Fundamental aspects of material boundaries in FDTD models were studied and quantified; FDTD algorithms were developed; the corresponding computer programs were written; and information was disseminated via journal publications, conference presentations, and the Web.

RESULTS

The FDTD method is obtained by discretizing the differential equations that govern the underlying system. Using a Cartesian grid, the method provides an exceedingly simple way in which to express

		Form Approved OMB No. 0704-0188
	Report Documentation Page	

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**

4. TITLE AND SUBTITLE **Numerical Studies of Acoustic Propagation in Shallow Water**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **School of Electrical Engineering and Computer Science,,Washington State University,P.O. Box 642752,,Pullman,,WA,99164**	8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

future fields (i.e., unknown fields) in terms of past fields (known fields). For propagation in a homogeneous region, the traditional FDTD method is accurate to second-order---doubling the number of grid points per wavelength reduces inherent numerical errors by a factor of four. However, the behavior and accuracy of field at material interfaces is much more complicated. We have derived exact expressions for the transmission and reflection coefficients for fields normally and obliquely incident on planar boundaries. Interestingly, it was found that the accuracy of the reflection and transmission coefficients is a function of the discretization used on either side of the boundary. Thus, although one may be interested only in the fields on one side of a boundary, a sufficiently fine discretization must be used on the other side to ensure that the reflection coefficient is accurate enough to prevent corruption of the fields in the region of interest. This work was reported at the 2000 IEEE AP-S International Symposium and URSI Radio Science Meeting [1].

In addition to our analysis of homogeneous plane wave interaction with material boundaries, we also studied the propagation of inhomogeneous plane waves in the FDTD grid. Inhomogeneous plane waves are important because they are required to form a complete basis set with which any field can be described. We derived the dispersion relation for inhomogeneous waves and showed that, in a lossless material, planes of constant phase are not necessarily orthogonal to planes of constant amplitude (as they must be in the continuous world). We showed how one could use the dispersion relation to determine exactly the behavior of evanescent fields in the FDTD grid when a wave is incident beyond the critical angle at a planar interface. We also firmly established several other characteristics of discretized worlds such as the inherent "grid velocity" (which is similar to Brillouin radiation in the continuous world). Part of this work was presented at the 1999 IEEE AP-S International Symposium and URSI Radio Science Meeting [2] and the entire work will appear in the February 2001 issue of IEEE Transactions on Microwave Theory and Techniques [3].

We have spent a great deal of effort exploring several new implementations of the FDTD method (proposed by others) which seek to minimize dispersive and anisotropic errors inherent in all 2- and 3-D FDTD schemes. We have developed comparisons that provide insights into the techniques that are not easily garnered from the publications that originally presented them. Preliminary work was reported at the 1999 IEEE AP-S International Symposium and URSI Radio Science Meeting [4] and a greatly expanded exploration has been submitted to IEEE Transactions on Microwave Theory and Techniques [5].

Previously we firmly established the ability of the FDTD method to model accurately scattering from randomly rough pressure-release surfaces. We have also made significant progress in establishing the use of FDTD methods for penetrable rough surfaces as described in a paper accepted for publication in IEEE Journal of Oceanic Engineering [6].

Similarly, we have developed a new FDTD scheme for the modeling of continuously varying rigid boundaries. This new scheme uses a locally conformal approach in that the usual FDTD update equations apply everywhere away from the boundary. For points adjacent to the boundary, modified equations are used. This scheme is "low cost" since the coefficients used in the modified update equations can be calculated in a preprocessing stage. We have shown that this scheme signficantly improves the accuracy over that obtained using a traditional stair-step representation of the boundary. This work will be reported at the December 2000 ASA Meeting.

We maintain a Web site, www.fdtd.org, that seeks to list all archival publications related to the FDTD method. This site was completely redesigned with the goal of drawing input from the entire community

interested in the FDTD method (whether applied to acoustics, electromagnetics, or solid mechanics). The site now allows user registration, comments on citations, notification of comments, etc. The redesigned site has come on-line only recently and is still in a state of flux while the FDTD community makes suggestions concerning desired additional functionality. We anticipate adding special sections to the site that highlight the application of FDTD to acoustics and to solid mechanics. (This site was started under NSF funding but also acknowledges support by ONR.)

Code was written to implement various components of a complete package for acoustic FDTD simulations. This code was carefully written to ensure that it is modular, efficient (both in terms of CPU cycles and memory), robust, and accurate. Previously we generated thousands of lines of code that typically served as one-of-a-kind programs for proof-of-concept research endeavors, i.e., quick and dirty code. Now, having established many of these concepts, we are translating the concepts into production-quality code that we hope to distribute openly. Our goal here is to have a library of FDTD programs---together with supporting code for visualization and interpretation---that can be used easily by people with varying degrees of programming or FDTD experience. This code will be distributed through www.fdtd.org.

IMPACT/APPLICATIONS

Accurate and flexible numerical methods allow researchers to conduct any number of experiments without having to resort to actual field experiments, i.e., the experiment is conducted on the computer. Although numerical methods will never supplant field experiments, numerical methods (when used within their "region of validity") do provide an extremely cost-effective means of conducting controlled experiments. Our work will enable more accurate and more efficient numerical solutions to a wide range of problems in acoustics, electromagnetics, and continuum mechanics.

TRANSITIONS

Much of the knowledge we have gained has been disseminated via publications and conference presentations. Additional material is available via the Web. Please refer to the Web site given in the header for copies of the PI's publications or www.fdtd.org for other material pertinent to the FDTD method.

RELATED PROJECTS

This work is related to research in both high-frequency acoustics and long-range propagation. Numerical models, such as the FDTD method, can be used to predict the fields scattered from small objects under short-wavelength insonification or the propagation of long-wavelength signals over limited regions of the ocean. Additionally, this work is related to of several other ONR-sponsored researchers including Shira Broschat, Eric Thorsos, and Philip Marston.

PUBLICATIONS

1. J. B. Schneider and R. J. Kruhlak, "Plane Waves and Planar Boundaries in FDTD Simulations ," IEEE AP-S International Symposium and URSI Radio Science Meeting, Salt Lake City, UT, Jul. 2000.

2. J. B. Schneider and R. J. Kruhlak, "Inhomogeneous Waves and Faster-than-Light Propagation in the Yee FDTD Grid," IEEE AP-S International Symposium and URSI Radio Science Meeting, vol. 1, pp. 184--187, Orlando, FL, Jul. 1999.

3. J. B. Schneider and R. J. Kruhlak, "Dispersion of Homogeneous and Inhomogeneous Waves in the Yee Finite-Difference Time-Domain Grid," to appear in IEEE Trans. Microwave Theory and Techniques, Feb., 2001.

4. K. L. Shlager and J. B. Schneider, "Relative Accuracy of Several Low-Dispersion Finite-Difference Time-Domain Schemes," IEEE AP-S International Symposium and URSI Radio Science Meeting, vol. 1, pp. 168--171, Orlando, FL, Jul. 1999.

5. K. L. Shlager and J. B. Schneider, "Comparison of the Dispersion Properties of Several Low-Dispersion Finite-Difference Time-Domain Algorithms" submitted to IEEE Transactions on Microwave Theory and Techniques.

6. F. D. Hastings, J. B. Schneider, S. L. Broschat, and E. I. Thorsos, "An FDTD Method for Analysis of Scattering from Rough Fluid-Fluid Interfaces" submitted to IEEE Journal of Oceanic Engineering.